Determining Vibro-Acoustic Effects in Multidomain Systems using a Custom Simscape Gear Library

Tim Dackermann, Rolando Dölling
Robert Bosch GmbH

Lars Hedrich
Goethe-University Ffm

Power transmission

Combustion engine

…

Gearing

…

Tires & vehicle

Pictures: [1]

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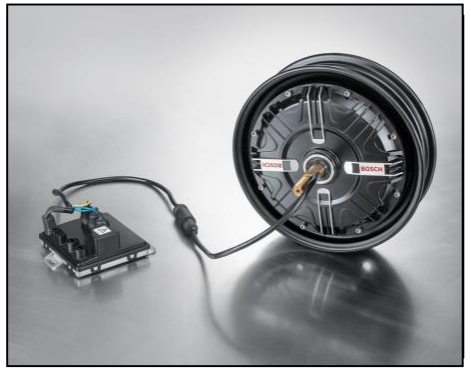
Noise emission



Electric motor

…

Gearing

…

Tires & vehicle

Pictures: [1]

Noise emission

Goal 1 → **Analysis**

Goal 2 → **Optimization**

Goal 3 → **Prediction**

Multidomain System Modeling

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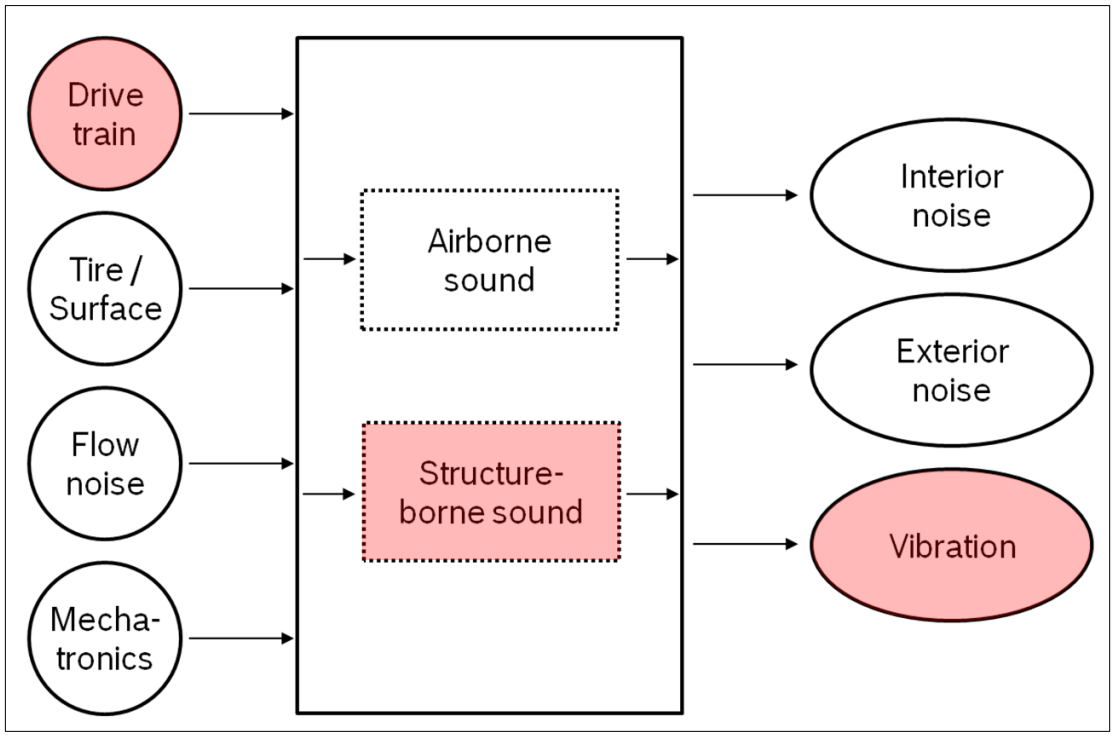
Outline

- Vibro-acoustic sources and transmission paths
- Requirements for a vibro-acoustic gear model
- Mechanical excitation mechanisms
- **Flexible gear model library in SimMechanics**
  - Idea and concept
  - Implementation
  - Application
- Conclusions

[1]

Vibro-acoustic sources and transmission paths

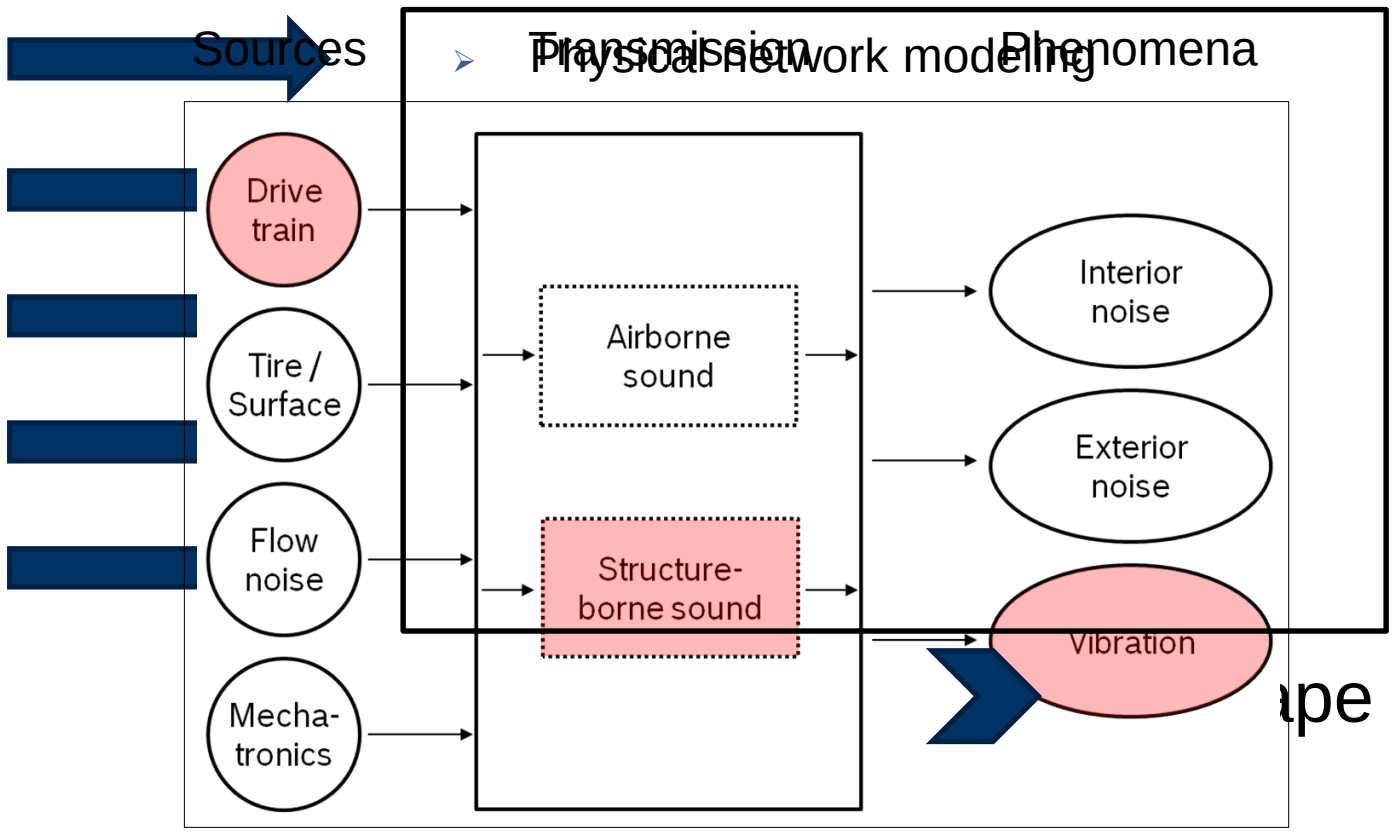
[1]



[2]

Requirements for a vibro-acoustic gear model

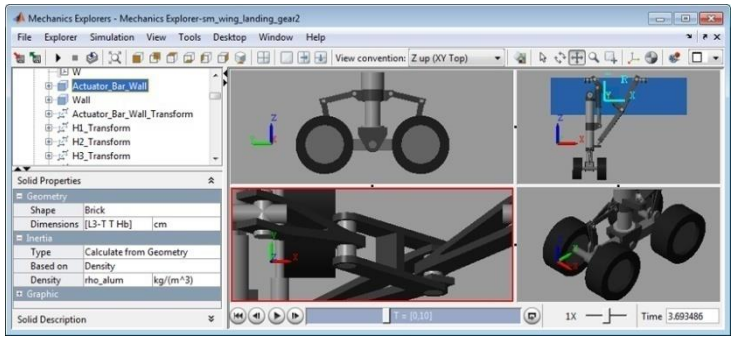
- Multidomain simulation
- Simple model usage
- Model extension
- Efficient simulation
- Three-dimensional gear mesh excitation

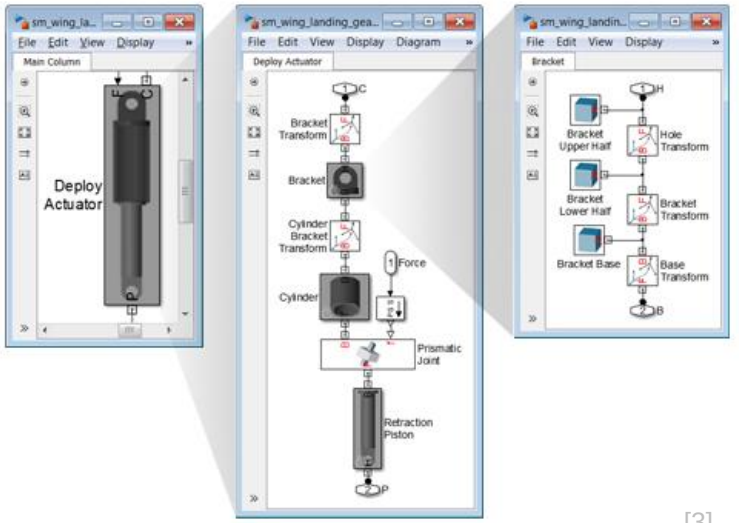


[2]

SimMechanics™

- Multibody simulation environment
- 3D mechanical systems
- Cross-domain simulation
- Visualization and animation
- Interfaces to CAD-software





[3]

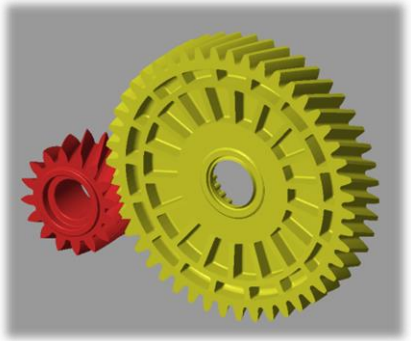
SimMechanics™ – Common Gear Constraint

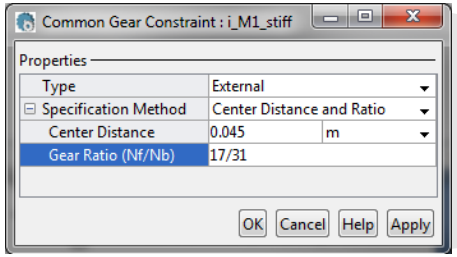
MathWorks

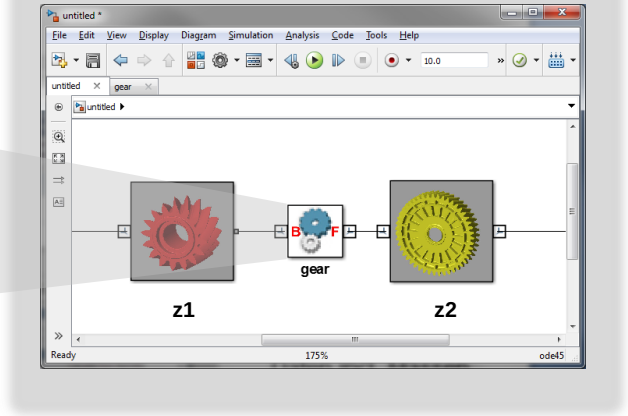
Common Gear Constraint

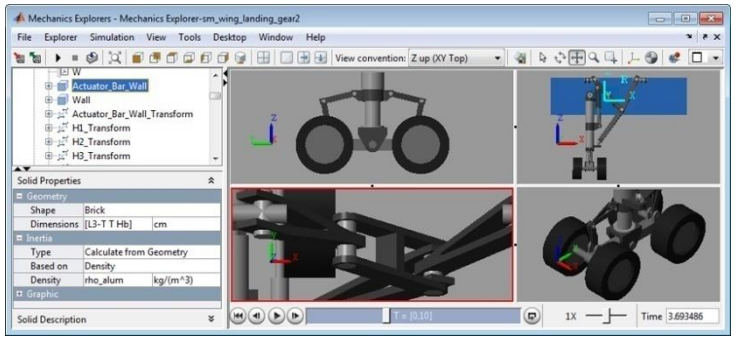
$$\varphi_1 \cdot r_1 + \varphi_2 \cdot r_2 = 0$$

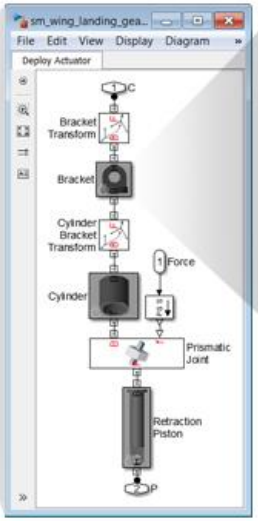
Need for an advanced gear model!

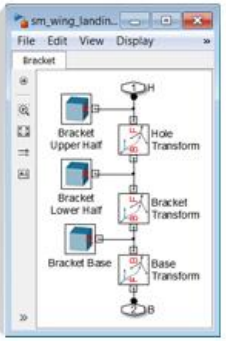












[3]

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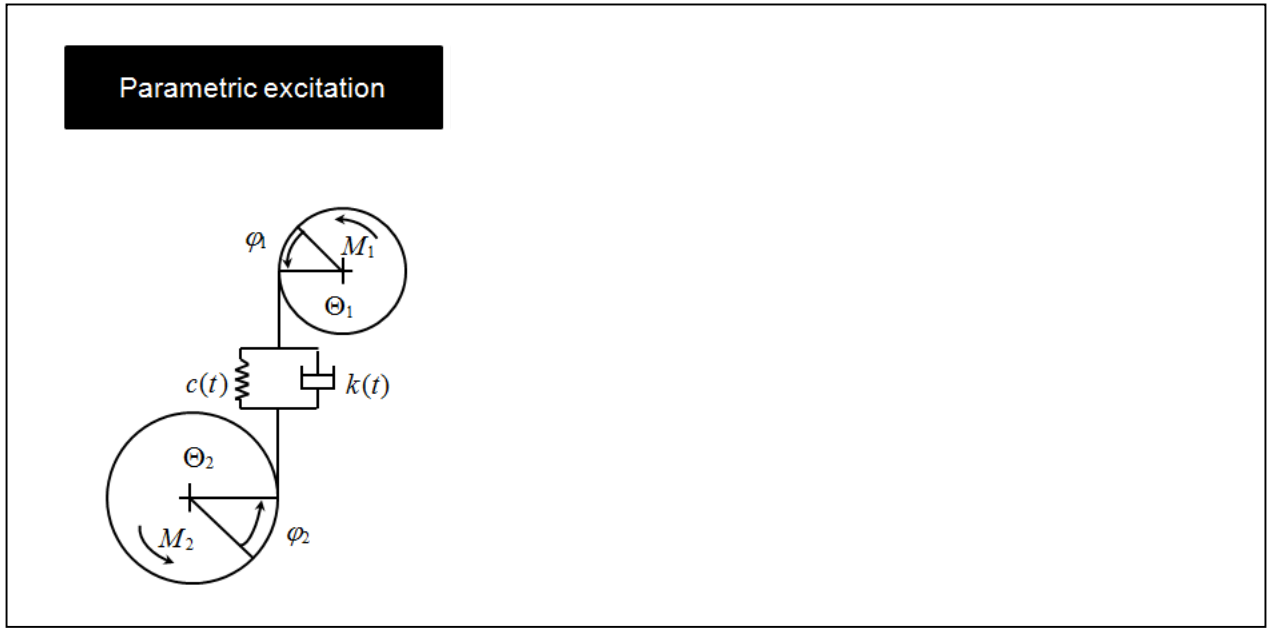
Vibro-acoustic sources within a gear

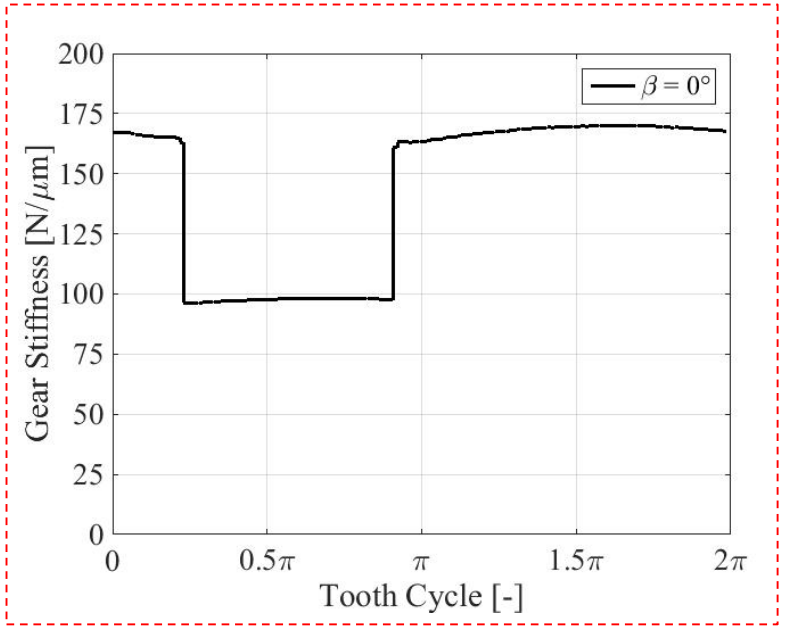
Mechanical excitation mechanisms

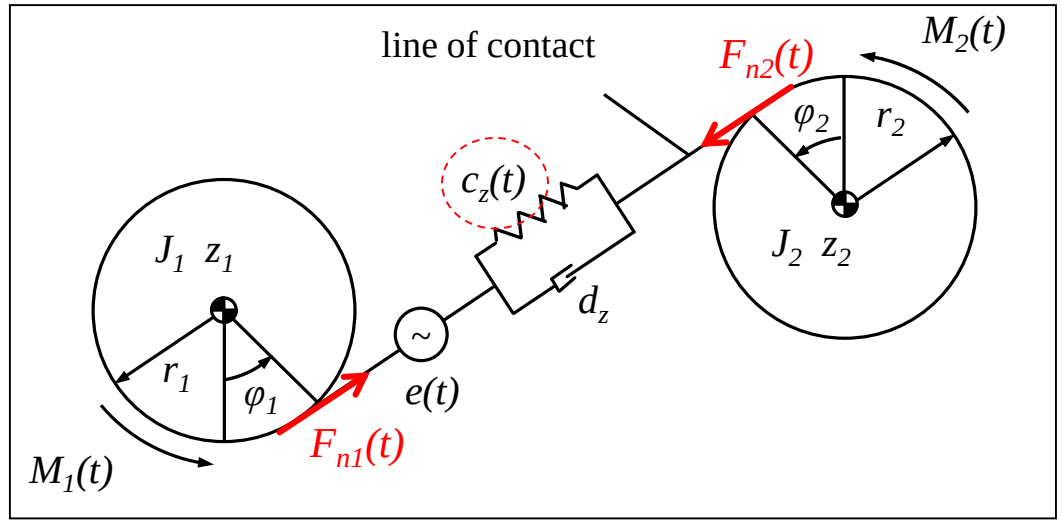


[4]

- Parametric excitation
- Geometric excitation
- Impulse excitation

Mathematical characterization of a lumped parameter gear model





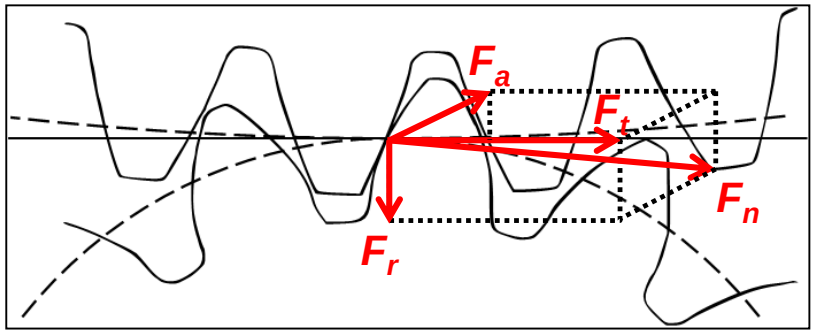
[5]

Formulation of a dynamic mathematical gear model

Mathematical characterization of a LPM gear model

F_t: *Tangential force*
F_r: *Radial force*
F_a: *Axial force*
F_n: *Tooth normal force*

α_n : *Normal pressure angle*
β : *Helix angle*



[5]

Calculation

$$M_1 = F_t \cdot r_1 \qquad (1)$$

$$F_t = F_n \cdot \cos(\beta) \cdot \cos(\alpha_n) \qquad (2)$$

(1) and (2):

$$F_n = \frac{M_1}{r_1 \cdot \cos(\beta) \cdot \cos(\alpha_n)}$$

$$\begin{bmatrix} F_t \\ F_r \\ F_a \end{bmatrix} = A_\beta A_{\alpha_n} \begin{bmatrix} F_n \\ 0 \\ 0 \end{bmatrix}$$

Rotational matrixes

$$A_\beta = \begin{pmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{pmatrix}$$

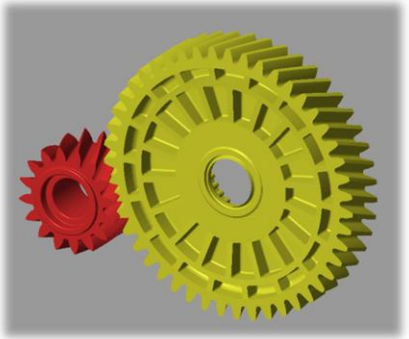
$$A_{\alpha_n} = \begin{pmatrix} \cos\alpha_n & -\sin\alpha_n & 0 \\ \sin\alpha_n & \cos\alpha_n & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

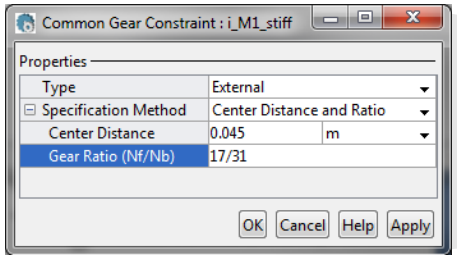
SimMechanics™ - Common Gear Constraint

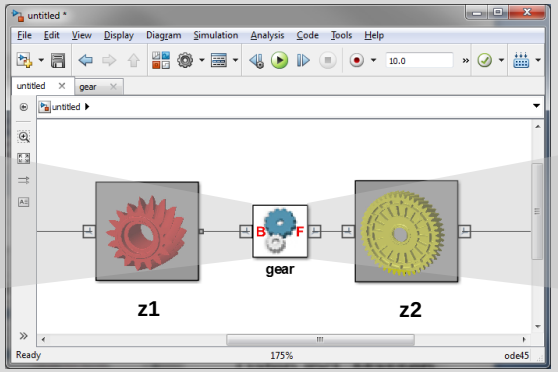
Common Gear Constraint

$$\varphi_1 \cdot r_1 + \varphi_2 \cdot r_2 = 0$$

Kinematic constraint





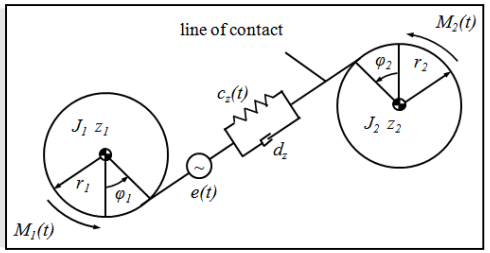


Flexible Gear Model

$$\varphi_1 \cdot r_1 + \varphi_2 \cdot r_2 = TE$$

e.g. [6,7]

Additional degree of freedom



[5]

Library extension enables transmission error (TE) and gear force calculation

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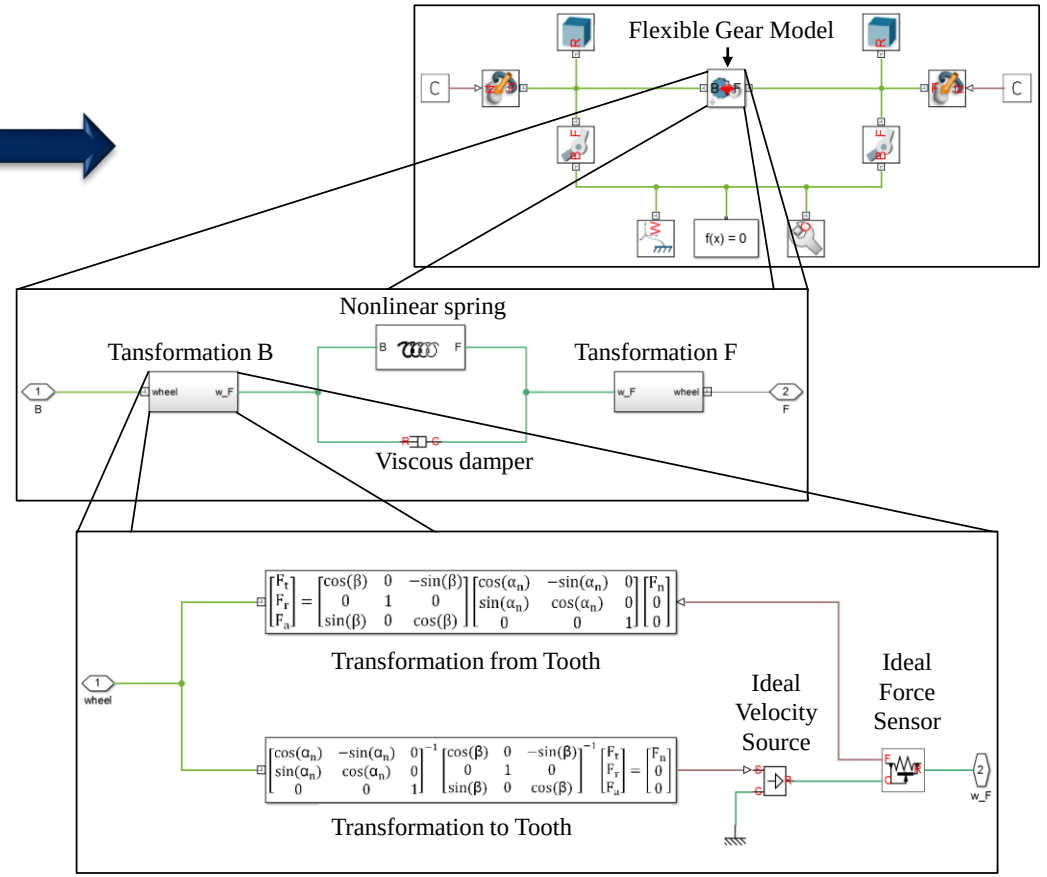
SimMechanics™ - Flexible Gear Model

System level

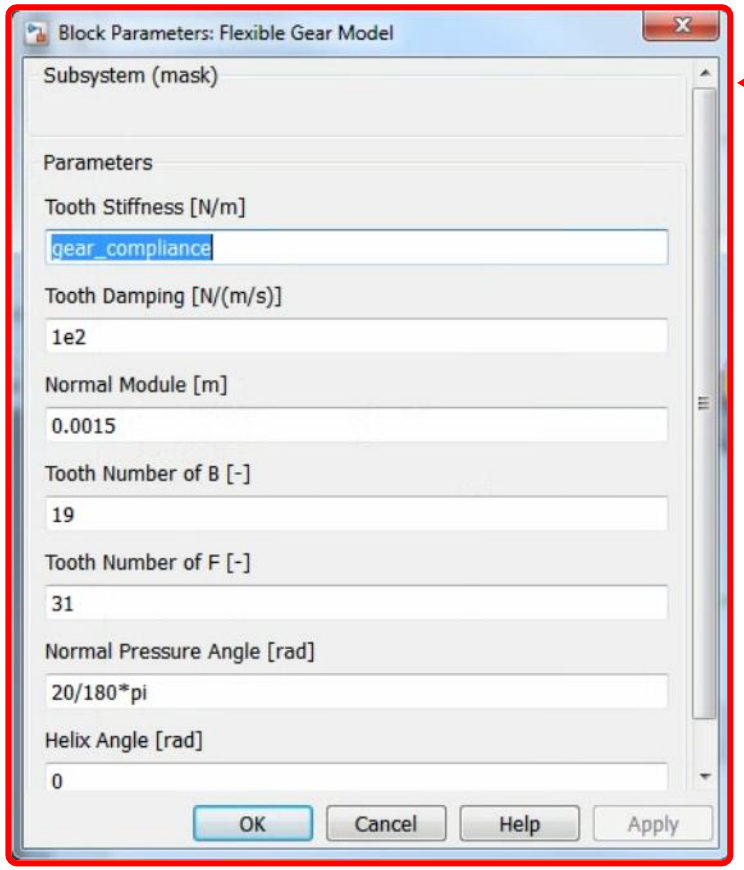
Coupling layer

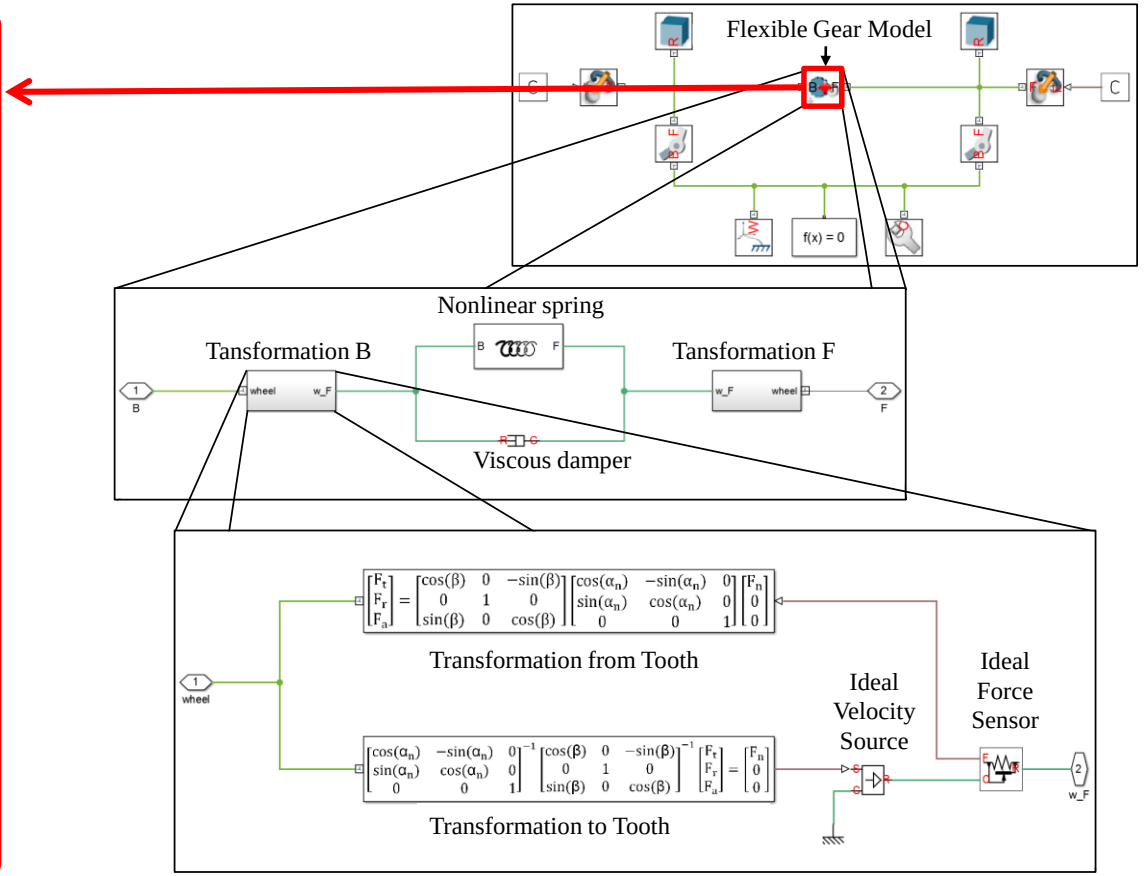
Transformation



[5]

SimMechanics™ - Flexible Gear Model





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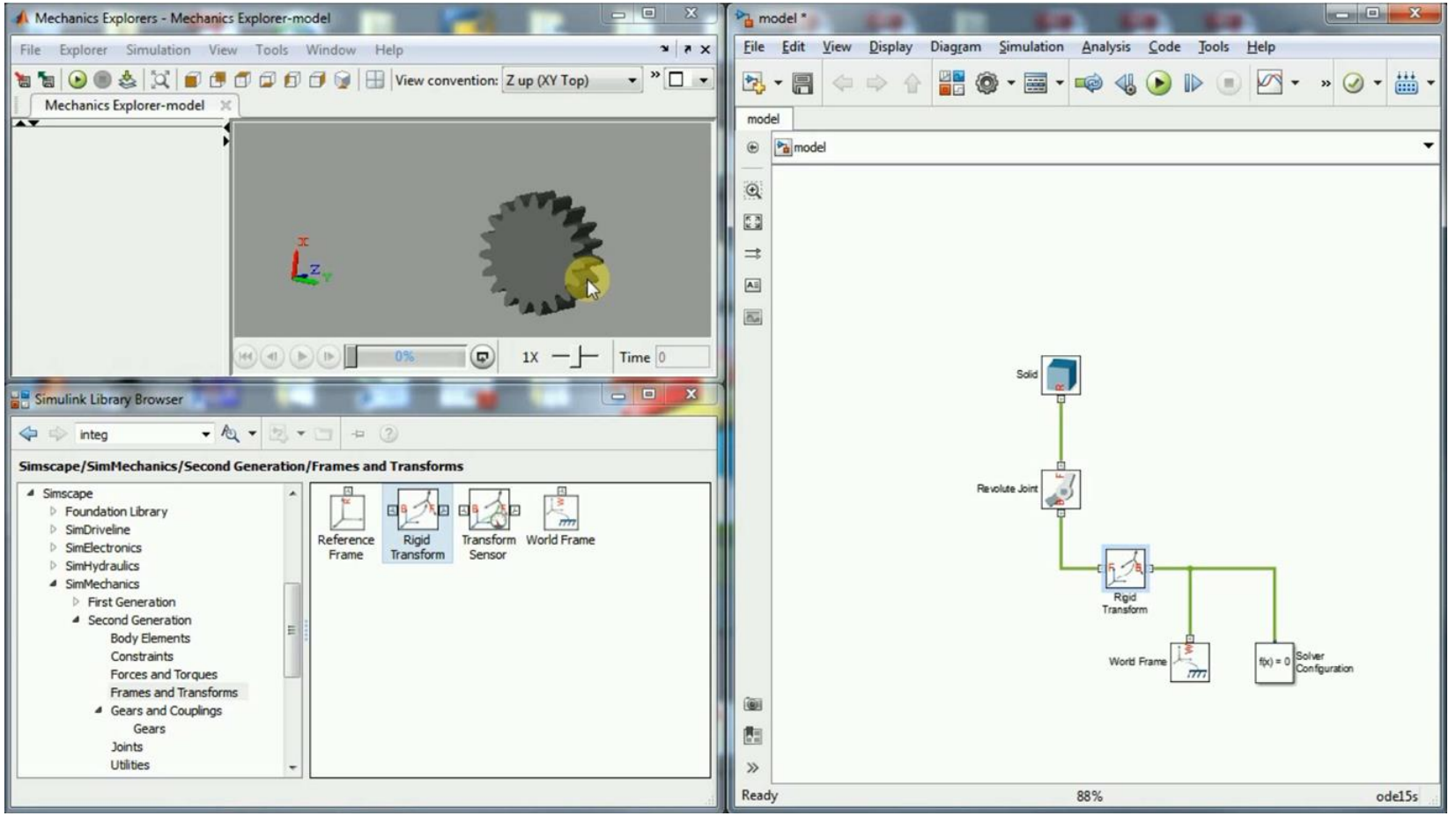
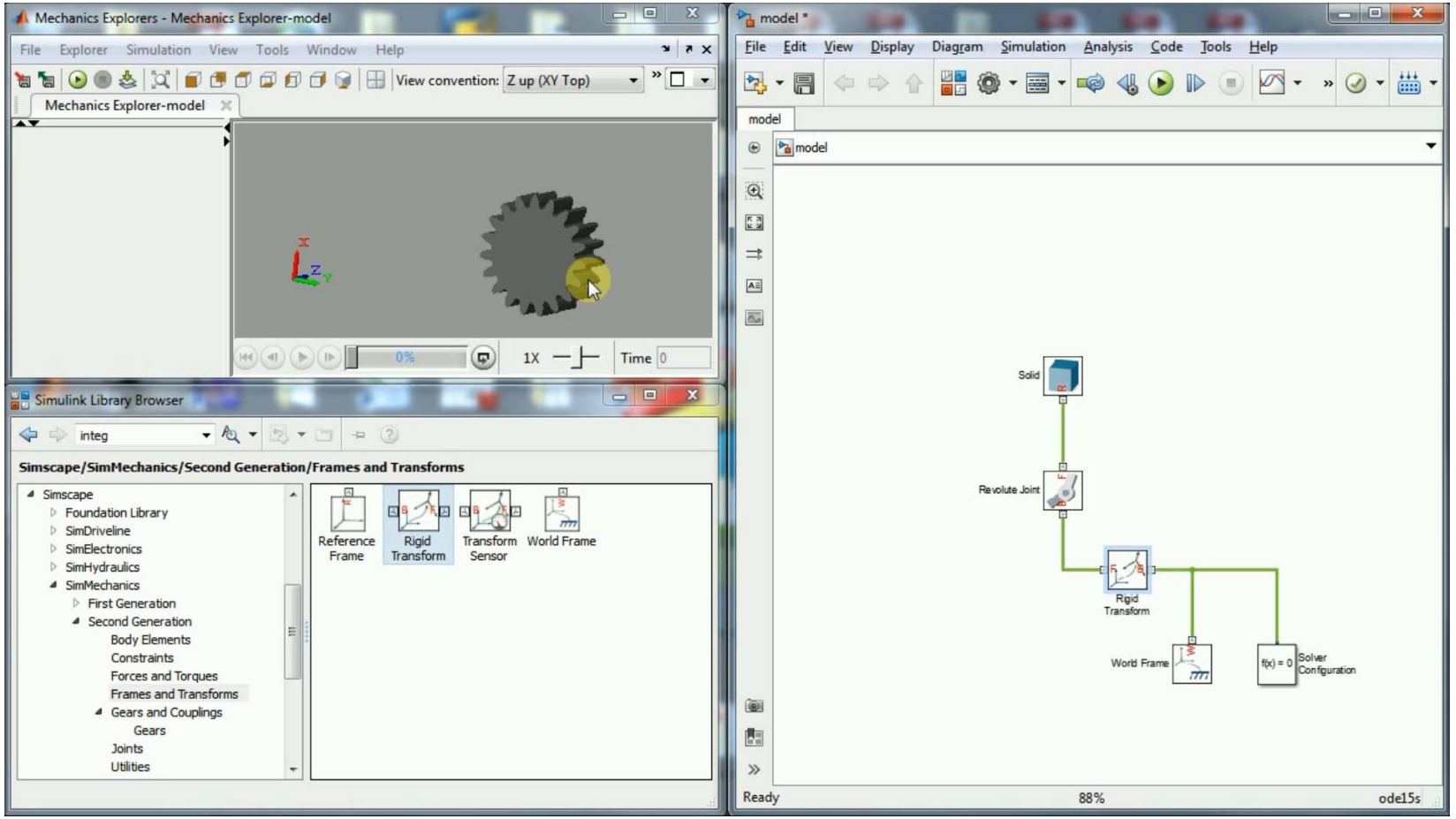
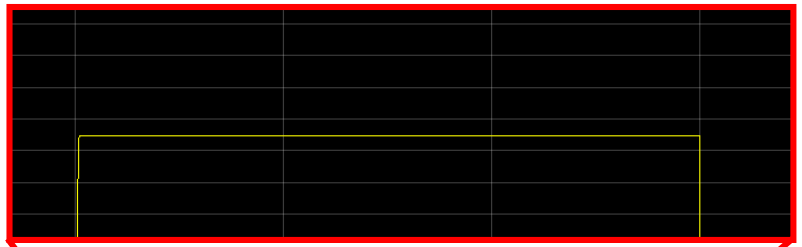
SimMechanics™ - Flexible Gear Model



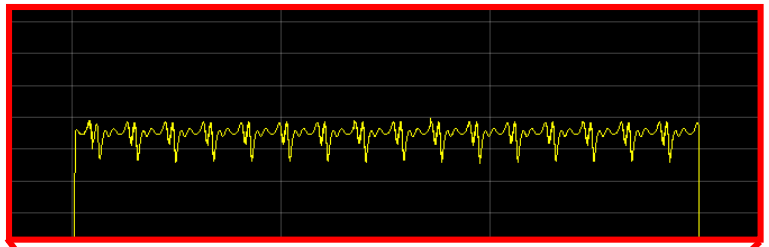
SimMechanics™ - Flexible Gear Model



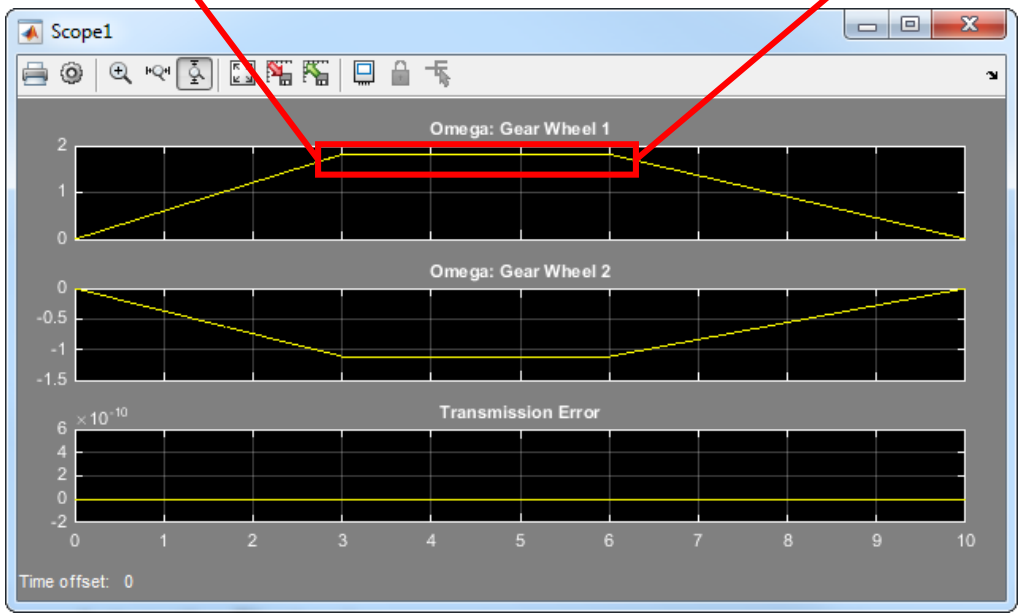
SimMechanics™ - Flexible Gear Model - Analysis

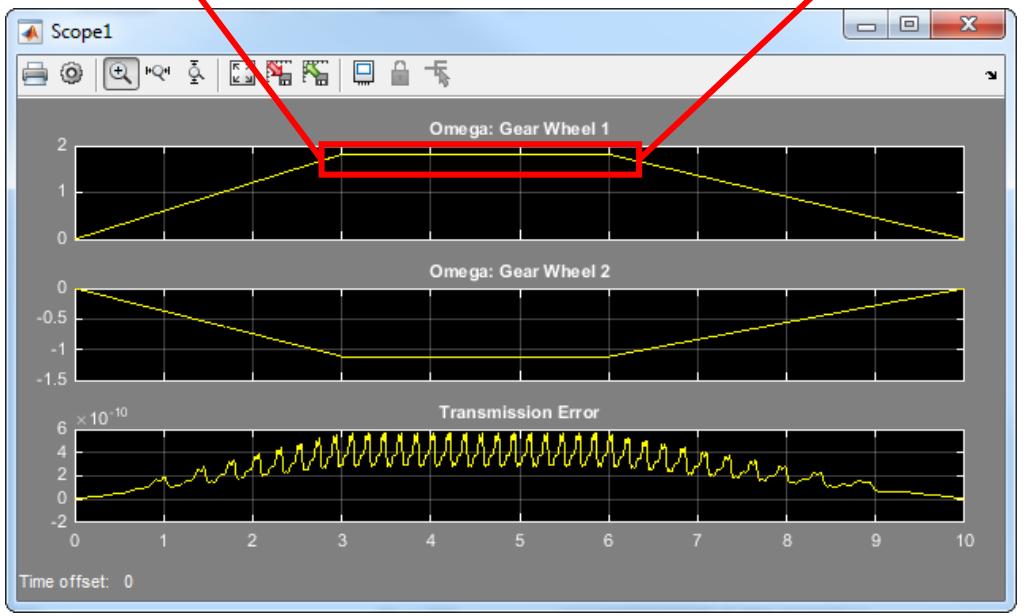


Common Gear Constraint

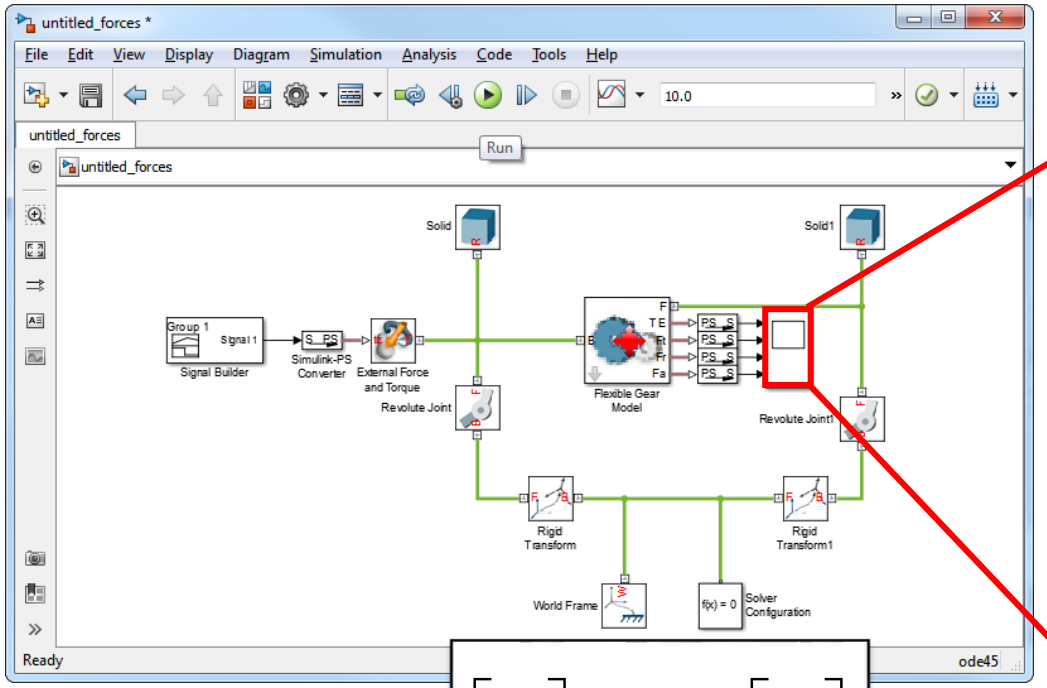


Flexible Gear Model

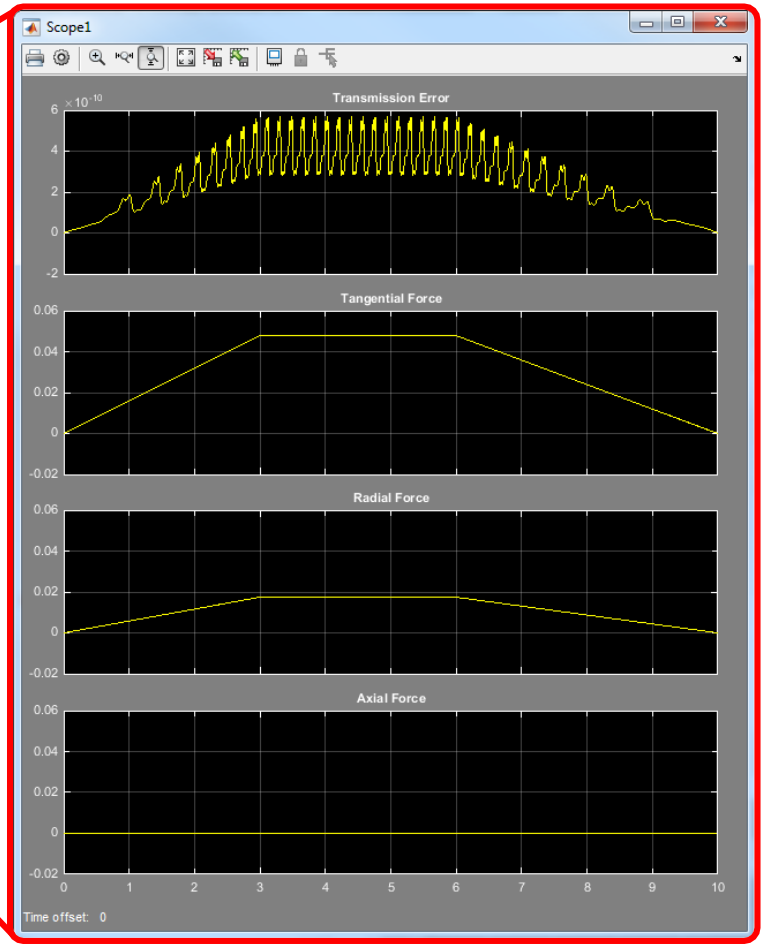




SimMechanics™ - Flexible Gear Model - Analysis

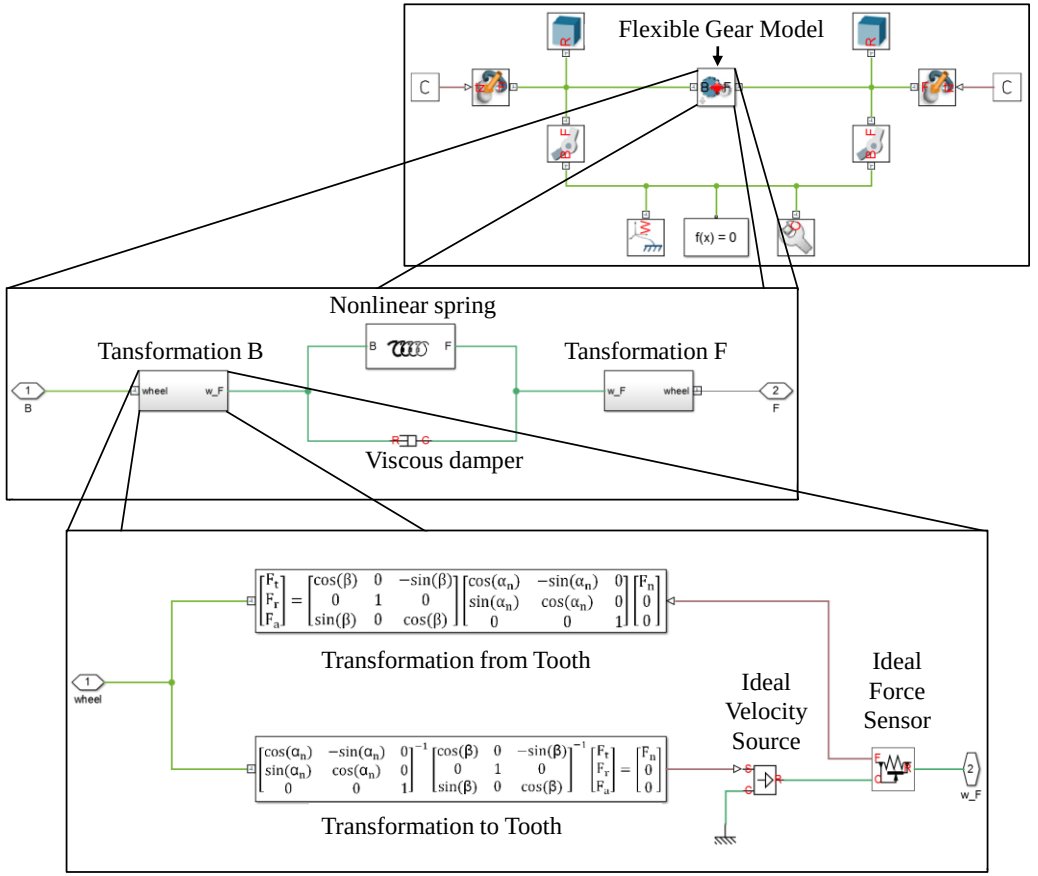


$$\begin{bmatrix} F_t \\ F_r \\ F_a \end{bmatrix} = A_\beta A_{\alpha_n} \begin{bmatrix} F_n \\ 0 \\ 0 \end{bmatrix}$$



Conclusions

- Implementation of a modular flexible gear model
- Three-dimensional gear mesh excitation
- Calculation of TE
- Calculation of gear forces



[5]

Further information regarding gear modeling

Flexible Gear Model Library - Vibration Excitation Mechanisms and Gear Force Calculation

T. Dackermann, S. Miller, L. Hedrich, Rolando Doelling, Modelling, Identification and Control, Computational Intelligence, MIC, 826-010, Innsbruck, February 2015

- More details concerning the Simscape gear library
- Some results of verification

Method for system level vibro-acoustic gear modeling and simulation of electro-mechanical drive trains

T. Dackermann, Rolando Doelling, L. Hedrich, IEEE International Symposium on Systems Engineering (ISSE), Rom, September 2015

- Heterogeneous system modeling and vibro-acoustic gear simulation
- Flexible housing and airborne sound emission
- Validation of model by means of measurements

Images and literature sources

[1] Bosch GmbH, http://www.bosch.com

[2] P. Zeller, *Handbuch Fahrzeugakustik: Grundlagen, Auslegung, Berechnung, Versuch* (ATZ/MTZ-Fachbuch) Gebundene Ausgabe – 14. Mai 2009

[3] MathWorks, http://www.mathworks.com/

[4] A. Gacka, *Entwicklung einer Methode zur Abbildung der dynamischen Zahneingriffsverhältnisse von Stirn- und Kegelradsätzen*, Bericht aus der Produktionstechnik, Shaker Verlag, 2013

[5] T. Dackermann, S. Miller, L. Hedrich, Rolando Doelling, *Flexible Gear Model Library - Vibration Excitation Mechanisms and Gear Force Calculation*, Modelling, Identification and Control, Computational Intelligence, MIC, 826-010, Innsbruck, February 2015

[6] M. Henriksson, *On noise generation and dynamic transmission error of gears,* ISBN 978-91-7415-537-2, Stockholm 2009

[7] D. R. Housser et al., *Comparison of transmission error predictions with noise measurements for several spur and helical gears*. National Aeronautics and Space Administration, 1994.